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SIMULATION OF PRESTRESSED CONCRETE SANDWICH PANELS SUBJECTED TO BLAST LOADS

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14. ABSTRACT
This paper discusses simulation methodology used to analyze static and dynamic behavior of foam insulated concrete sandwich wall panels through ultimate capacity. The experimental program used for model development and validation involved component-level testing, as well as both static and dynamic testing of full-scale wall panels. The static experiments involved single spans and double spans subjected to near-uniform distributed loading. The dynamic tests involved spans up to 30 ft tall that were subjected to impulse loads generated by an external explosion. Primary modeling challenges included: (1) accurately simulating prestressed initial conditions in an explicit dynamic code framework, (2) simulating the foam insulation in the high strain rate environment, and (3) simulating shear transfer between wythes, including frictional slippage and connector rupture. After validation, the models will be used to conduct additional behavioral studies and parametric analyses, and assess and improve methodology currently used in the design of foam insulated precast/prestressed sandwich panels for blast loads.

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prestressed concrete, sandwich panels, simulation, LS-DYNA, blast, tilt-up panels

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Simulation of Prestressed Concrete Sandwich Panels Subjected to Blast Loads

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Design and Behavior of Prestressed Concrete Subjected to Blast and Impact Loading

ABSTRACT

This paper discusses simulation methodology used to analyze static and dynamic behavior of foam insulated concrete sandwich wall panels through ultimate capacity. The experimental program used for model development and validation involved component-level testing, as well as both static and dynamic testing of full-scale wall panels. The static experiments involved single spans and double spans subjected to near-uniform distributed loading. The dynamic tests involved spans up to 30 ft tall that were subjected to impulse loads generated by an external explosion. Primary modeling challenges included: (1) accurately simulating prestressed initial conditions in an explicit dynamic code framework, (2) simulating the foam insulation in the high strain rate environment, and (3) simulating shear transfer between wythes, including frictional slippage and connector rupture. After validation, the models will be used to conduct additional behavioral studies and parametric analyses, and assess and improve methodology currently used in the design of foam insulated precast/prestressed sandwich panels for blast loads.

INTRODUCTION

Background. Threats to structures and the people residing within are increasing. Since the attacks on the World Trade Center and the Pentagon on September 11, 2001, the realization of such threats has promoted research in the field of structures subjected to impulse loads. The study of structures subjected to impulse loads has existed for decades; however, a shift in the type of risks structures faced has occurred due to the more localized manner of current threats.

The behavior and design of structural components subjected to impulse loads differs from the behavior under static loads. Most loads such as wind and gravity loads are assumed to be static since the time in which they are applied is relatively large enough not to induce accelerations of structural components. Dynamic loads such as blasts last only a fraction of a second but may be quite large in magnitude. The design of structural components for impulse loads is also different from design for static loads in that failure of the structural component may be acceptable depending upon how the component failed. The primary goal in blast design is the safety of the people residing within the structure.

A common type of modern exterior wall construction, the sandwich panel, is comprised of two concrete wythes separated by a layer of foam insulation. The concrete wythes can be either conventionally reinforced or prestressed. Reinforcement allows the concrete to reach its full flexural strength and resist lateral loads and construction and handling loads. Since these wall structures also serve the purpose of insulating the building, it is common for ties that connect concrete wythes to each other to be made of non-metallic materials (PCI, 2004).

Objective. The overall objective of the effort was to develop high fidelity finite element (FE) modeling methodologies for simulating precast insulated concrete sandwich panels, and to use the models to improve understanding of the ultimate strength behavior of precast /prestressed sandwich panels under blast loads.

Scope and Methodology. Due to the high costs associated with full-scale dynamic tests, the use of finite element models is crucial to understanding failure modes, energy dissipation, and damage of sandwich panels subjected to blast loads. Loading tree tests conducted at the University of Missouri were used to validate the FE modeling approach and input parameters. Static tests used for validation consisted of (1) simple reinforced concrete beams, (2) conventionally reinforced sandwich panels, and (3) prestressed sandwich panels. Also, shear tests involving a variety of connectors were conducted to assess the shear transfer through ties and its impact on composite action. High fidelity, dynamic FE models were developed and full-scale dynamic tests conducted by the Air Force Research Laboratory (AFRL) were used to validate the dynamic analysis approach. Once the dynamic FE models have been validated, a parametric study will ensue that will explore the effects of varying design attributes, loading, and boundary conditions on key sandwich panel behavioral phenomena such as energy attenuation, failure modes, and damage. This paper focuses on modeling methodology, validation approach, and challenges, and does not report details of the dynamic tests conducted by AFRL.

STATIC MODELING AND VALIDATION

The primary challenges associated with FE modeling of foam-insulated concrete sandwich panels include: accurately describing and incorporating the fracture and damage behavior of reinforced concrete, integrating foam constitutive models, accurately describing the transfer of shear between concrete wythes, incorporating strain rate effects on material behavior, and simulating initial conditions associated with the prestressed steel strands. Validation of input parameters was accomplished in three parts: (1) simple reinforced concrete beams subjected to uniform loading, (2) static testing of sandwich panels (prestressed and conventionally reinforced) subjected to uniform loading, and (3) full-scale dynamic tests of sandwich panels (prestressed and conventionally reinforced). Component and material level test results were used to define appropriate constitutive model input. Direct shear tests were used to evaluate the shear resistance input required to simulate the various ties used in the full-scale sandwich panels.

Reinforced Concrete Beam Validation Testing. Three conventionally reinforced concrete beam designs were tested under a near-uniform distributed load using the University of Missouri loading tree apparatus. All samples were 18 inches wide, simply supported, with a 144 inch clear span. Three samples of each design were constructed and total load and midspan vertical displacement were recorded for each sample. The test matrix and reinforcement description are provided in Table 1.

Static FE Modeling of the Reinforced Concrete Beam Samples. ABAQUS was used to model the RC samples with the input parameters described in Table 2. The model uses a continuum, plasticity-based, damage model for concrete. It assumes that the primary two failure mechanisms are tensile cracking and compressive crushing of the concrete material.

Table 1. Description of Reinforced Concrete Beam Samples

Name	Depth (inch)	Reinforcement
RC 1, 2, & 3	11.5	Welded-Wire W4 x W4 @ 10” # 6’s @ 9.5”
RC 4, 5, & 6	11.5	# 8’s @ 9.5” # 8’s @ 2”
RC 7, 8, & 9	6	Welded-Wire W4 x W4 @ 3.25” # 4’s @ 3”

Table 2. Material Parameters of Concrete Damaged Plasticity Model

Concrete		Parameters of CDP Model	
E (psi) 3.6E+6		ψ , dilation angle	30°
Poisson's ratio v	0.18	ε , flow potential eccentricity	0.1
Density (pcf)	150	$\sigma_{b0} / \sigma_{c0}$ *	1.16
Compressive strength (psi)	4,000	K_c **	0.667
Tensile strength (psi)	300	μ , Viscosity parameter	0.0
Concrete Compression Hardening		Concrete Tension Stiffening	
Yield stress (psi)	Crushing strain	Remaining stress after cracking (psi)	Cracking strain
3,500 0.0		300	0.0
4,000 0.0005		0	0.002
2,500 0.0012		-	-

* The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress.
** The ratio of the second stress invariant on the tensile meridian, q (TM), to that on the compressive meridian, q (CM).

The rebar and welded wire reinforcement (WWR) were modeled explicitly with bar elements and metal plasticity models. The reinforcement mesh was superposed on the mesh representing the concrete continuum and assumed to be fully bonded. Parameters used for reinforcement are provided in Table 3. The rebar and WWR strength parameters were based upon laboratory testing of reinforcement samples used in construction of the samples. Strain hardening of the rebar was also included, with an ultimate strength of 107,120 psi. The stress/strain curve for the WWR was bilinear in nature with a failure strain of 0.02 in/in.

Table 3. Material Parameters for Rebar and WWR

	Modulus of elasticity (psi)	Poisson's ratio	Density (pcf)	Yield strength (psi)
Rebar 2.9E+7		0.3	490	69,710
WWR 2.9E+7		0.3	490	94,000

Figure 1 describes the FE models. The concrete was modeled using solid elements (C3D20; 20-node quadratic brick) and the reinforcement (rebar and WWR) was modeled with truss elements (T3D3; 3-node quadratic truss), respectively (HKS, 2006).

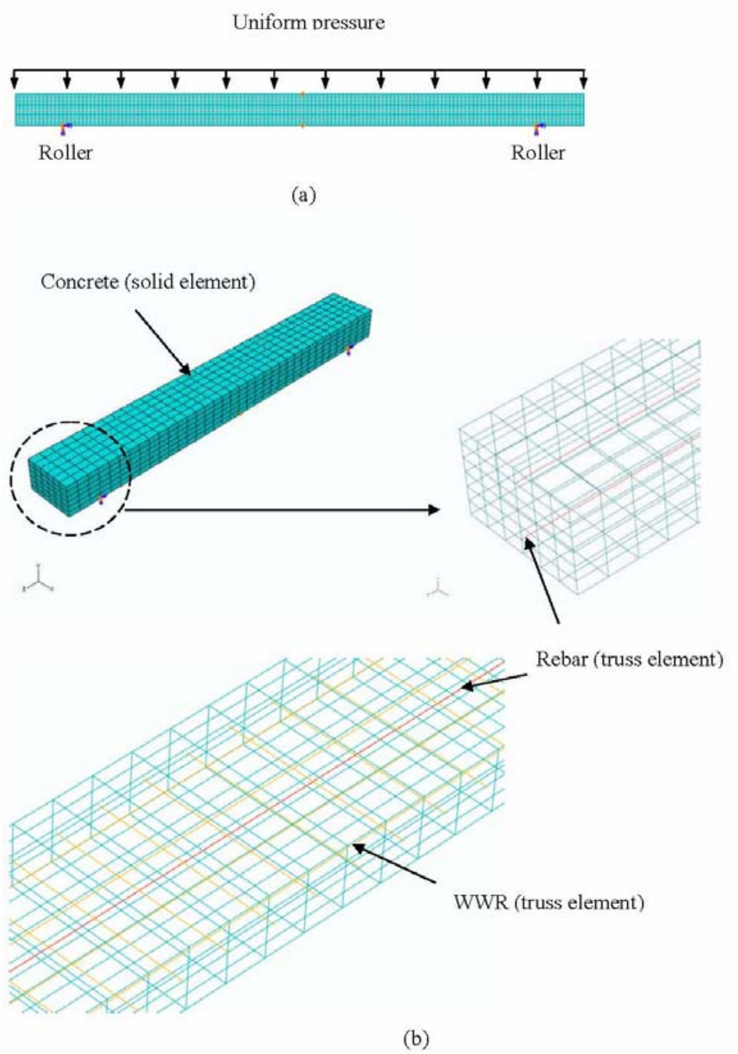

Figure 1. FE Models: (a) Loading and Boundary Conditions and (b) Concrete, Rebar and WWR Elements

Static RC Flexure Test and FE Results Comparison. As shown in Figures 2 through 4, the results from FE analyses were generally in good agreement with test results. RC 5 and RC6 did not yield usable test data. The initial stiffness of the FE models was slightly higher than that of the test beams, which is likely due to 1) cracking of samples that occurred prior to testing 2) seating of the support conditions during testing, and/or 3) approximations used for the compressive and tensile strength of the concrete. The difference in ultimate strength between RC4 and FE analyses is relatively large, which is likely due to the slippage of the tension bar within RC4.

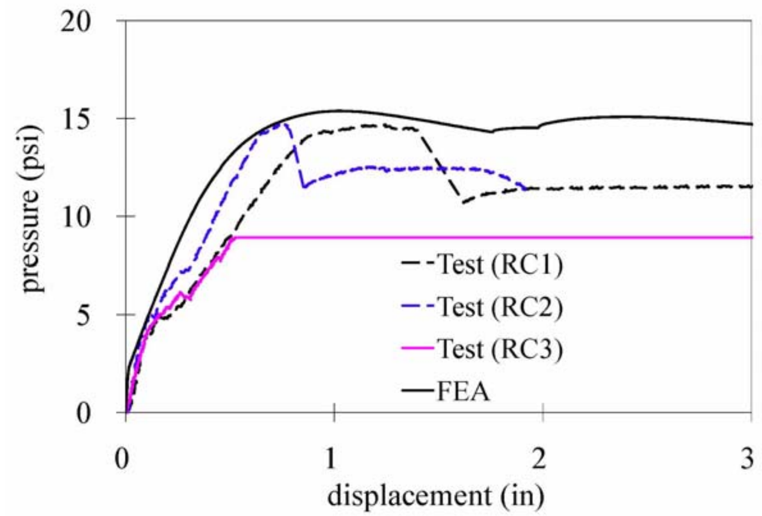

Figure 2. Tests (RC1, 2, 3) Versus FEA

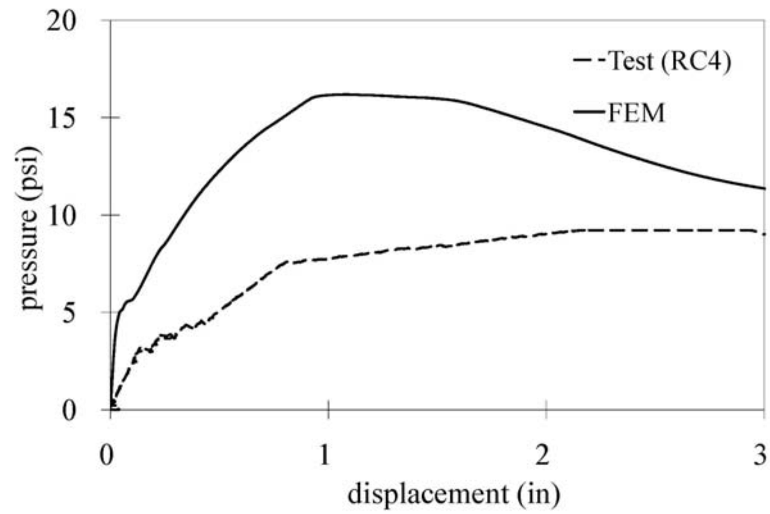

Figure 3. Tests (RC4) Versus FEA

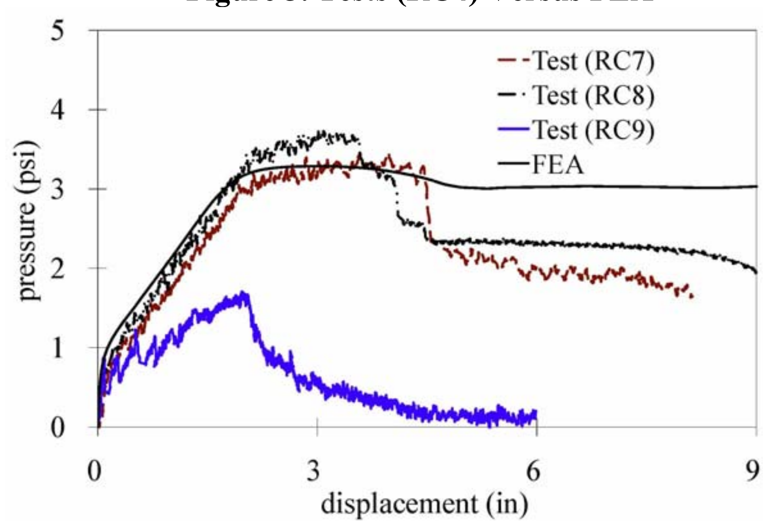

Figure 4. Tests (RC7, 8, 9) Versus FEA

Static Tests of Sandwich Panels. Static tests of prestressed and conventionally reinforced sandwich panels were also conducted under uniform distributed loading (Naito et al. 2009a). Important strength and stiffness design parameters included: configuration of concrete and foam layers, the type of foam used, and reinforcement (prestressed or conventional reinforcement). All prestressed sandwich panels had a 3-2-3 concrete-foam -concrete configuration. Conventionally reinforced panels had configurations of 3-2-3 a nd 6-2-3. Insulating foams included expanded polystyrene, extruded expanded polystyrene, and polyisocyanurate. Compressive testing of insulating foams used as construction materials was used to define the stress/strain material property input for foam elements (Jenkins 2008). An example of a conventionally reinforced static sandwich panel specimen is shown in Figure 5. Total load and vertical displacement of the midspan were recorded.

Shear Tie Tests. Static shear tie test results were used to define shear resistance of ties between the wythes of the sandwich panels. The testing configuration consisted of three concrete layers, two shear ties, and two layers of foam as shown in Figure 6. The symmetrical test configuration was chosen to minimize eccentricity. The outer two concrete wythes were fixed at the bottom, and the middle layer of concrete was pulled vertically. Total vertical load and vertical displacement were recorded. Extreme differences in resistances provided by commercially available shear ties were observed (Naito et al. 2009b).

Shear Tie Modeling Methodology. The results from the shear tie tests were used to establish multipoint constraint (MPC) input for tying the concrete wythes together. The direct shear tests were also modeled explicitly in ABAQUS as shown in Figure 7. A spring with a bilinear strength was used to model the axial resistance of the ties. The nonlinear SPRING1 elements were used to simulate the shear resistance of nodes coupled between wythes, and SPRING2 elements were used to simulate the axial behavior of ties. These models used the same concrete and rebar material properties as used for the RC models. Figure 8 illustrates that the MPC approach provides an efficient and accurate representation of the shear resistance of various sandwich panel ties.

Implementation of the MPC Approach into the Sandwich Panel Models. The MPC approached described above was incorporated into the sandwich panel models. A model simulating the loading tree was created in ABAQUS (Figure 9). The interface properties between concrete and foam did not include friction since the resistance data collected in the shear tie static tests indirectly includes friction resistance. The shear resistance of the 3-2-3 concrete sandwich panel, therefore, was provided by only nonlinear spring elements that represent each individual shear tie.

Figure 11 illustrates the comparison between the FE models and the static tests results of the 3-2-3 conventionally reinforced sandwich panel. The resistance decreased abruptly after reaching ultimate strength. This can be explained by the fact that several shear ties failed due to the slippage induced by the shear forces as shown in Figure 10, which clearly showed the slippage between the concrete and foam elements.

Simulation of Prestressing Effects in the Sandwich Panel Models. The approach used for modeling the prestressing strands was essentially the same as the procedures used for rebar in the reinforced concrete except that ABAQUS initial conditions features were used (*INITIAL CONDITIONS, TYPE=STRESS). The desired prestressing effects on the concrete element stresses were verified.

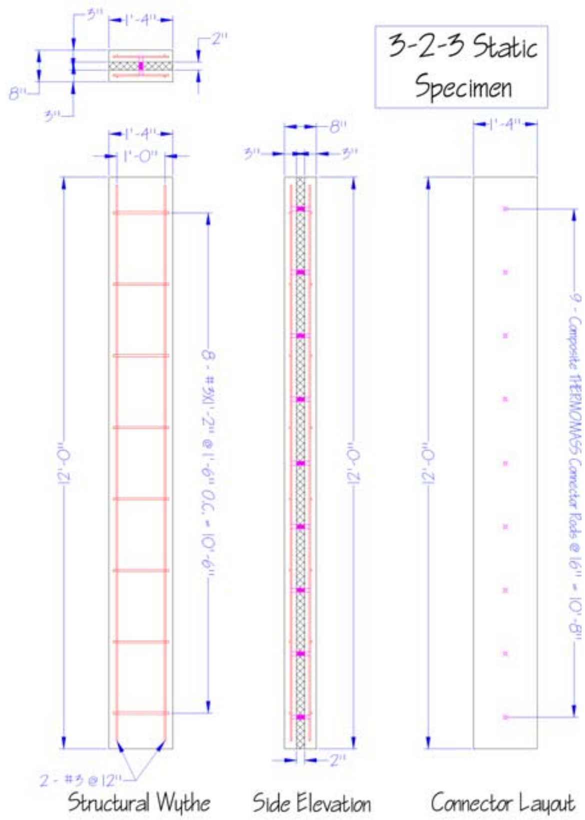

Figure 5. Conventionally Reinforced 3-2-3 Static Sandwich Panel Specimen

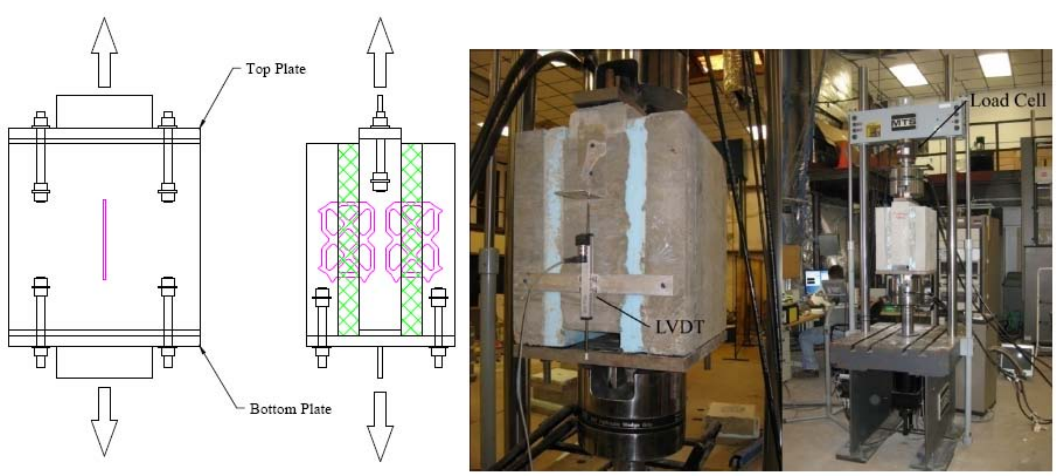

Figure 6. Shear Tie Static Test Configuration

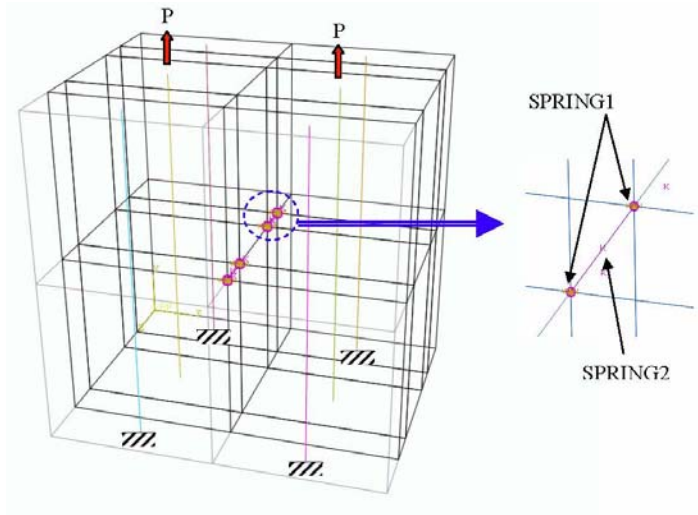

Figure 7. Shear Tie MPC Validation Model Configuration

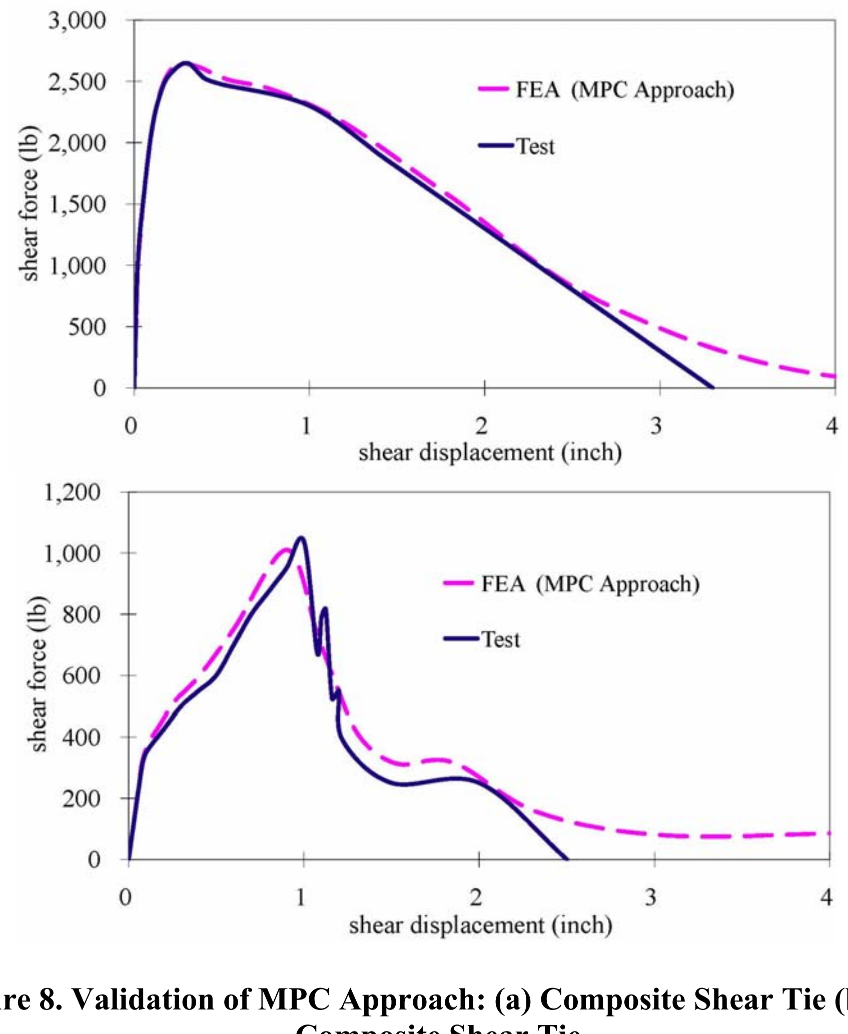

Figure 8. Validation of MPC Approach: (a) Composite Shear Tie (b) Non-Composite Shear Tie

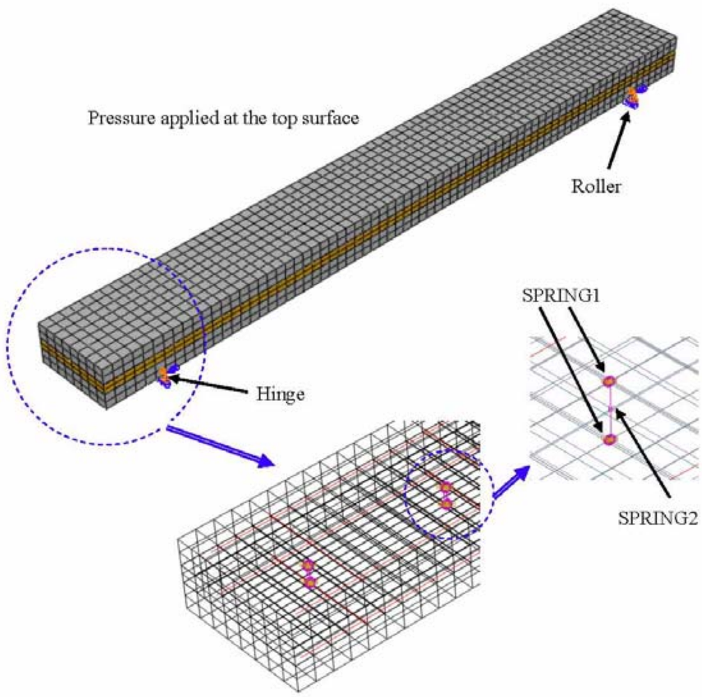

Figure 9. FE Model of Sandwich Panel Utilizing MPC for Shear Tie Behavior

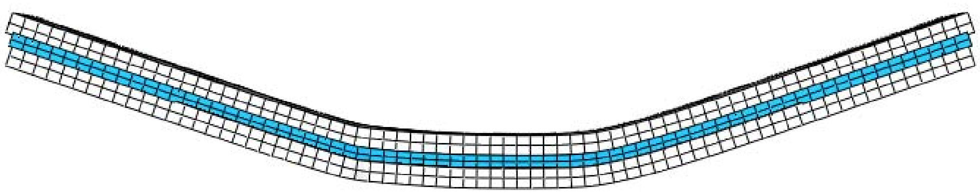

Figure 10. Deformed Shape of 3-2-3 Sandwich Panel Model Utilizing MPC Approach.

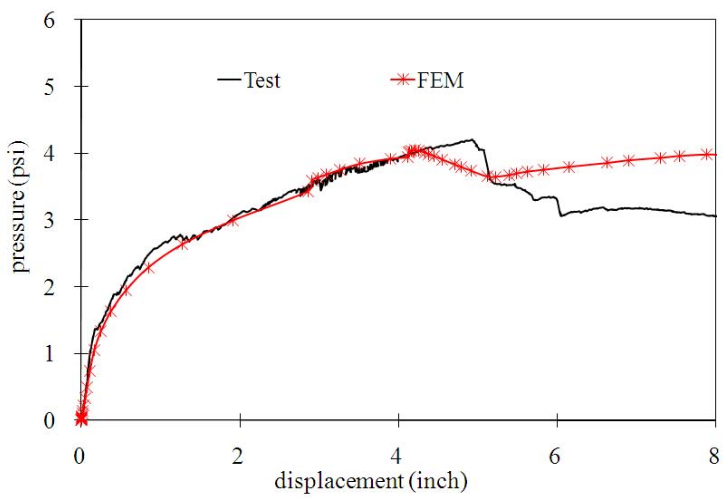

Figure 11. Comparison FE Model Utilizing MPC Approach with Static Test Data of the 3-2-3 Sandwich Panel.

DYNAMIC MODELING AND VALIDATION

Full-scale simply supported single span and two span sandwich panels were subjected to explosion-generated impulse loading. Figure 12 depicts the test arena used, with four single span and four double span panels shown ready for testing. Measured displacements and pressures are currently being used to validate dynamic models of both conventionally reinforced and prestressed sandwich panels. The validated models will be used in parametric studies for characterizing levels of protection.

Full-Scale Dynamic Test Modeling Approach. The FE element software LS-DYNA is being used for the dynamic models. In general, the modeling approach and input parameters used in the dynamic models are the same as used in the static models. For the prestressed sandwich panels, modeling methodology had to be developed to simulate prestressing effects prior to the application of transient loading. To accomplish this, the "dynamic relaxation" features of LS-DYNA were used, and the initial stress conditions in the concrete elements verified.

Figure 12. Test Arena Used for Full-scale Dynamic Testing

SUMMARY AND CONCLUSIONS

Finite element modeling is crucial to understanding failure modes, energy dissipation, and damage of sandwich panels subjected to blast loads. Uniform load static tests were used to validate FE modeling methodology. Static tests consisted of reinforced concrete beams, conventionally reinforced sandwich panels, and prestressed sandwich panels. Also, static tests of a variety of shear connectors were conducted to properly assess the shear transfer through ties and its impact on composite action.

Full-scale dynamic tests were used as points of validation for high fidelity, dynamic FE models. Once dynamic FE models have been validated, a parametric study of the panels will ensue, focusing on different geometries, loads, and boundary conditions. Analysis of the impact of such parameters will lead to understanding of important principles key to sandwich panel resistance such as energy dissipation, failure modes, and damage. Examination of dynamic FE models and current levels-of-protection will lead to recommendations for improving design methodology for precast/prestressed sandwich panels.

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